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(54) Title: NANOSTRUCTURE DEVICE AND APPARATUS

(57) Abstract

A nanodevice is disclosed wherein the gating member (150, 153'–157) can be either transverse to the conducting nanotube (150), or substantially surround the conducting nanotube (153'–157). A pseudo P–channel nanoswitch construction (150–151–152–153) as well as pseudo–CMOS nanoinverters (170–171–173–174–177–179) are disclosed and a nanomultivibrator (170–171–174–179–170'–171'–174'–179') and nanomultivibrator frequency dividing chain (174–190–190'–192–193) are disclosed operating in the sub–picosecond region. A pseudo P–channel enhancement mode power device (259, 259') is disclosed and is preferably used with an RC time constant compensation scheme (247i, 241i) to provide substantially simultaneous switching over the entire power nanoswitch (259, 259'). Nanotube separationand alignment apparati (300, 300') are disclosed, as well as improved atomic microscope probes (281–282–283–284–285–286–287, 291–292–293–294–295–297–298) and heads (310) to make and use the invention.

NANOSTRUCTURE DEVICE AND APPARATUS

TECHNICAL FIELD

The invention is in the solid state nanostructure device and atomic microscope apparatus fields.

BACKGROUND ART

U.S. Pat. 1,877,140 of September, 1932, to Lilienfeld and *Electronic Engineering Times,* November 16, 1998, p. 67, deal with nanostructures. Kasanuki et al., U.S. Pat., 5,418,771 and Yanagisawa et al., U.S. Pat.s 5,519,686 and 5,721,721, deal with atomic recording and microscope positioning technology. S. Tans et al., *Nature,* 3 April 1997, pp. 474-477, 7 May 1998, pp.49-52, and 20 August 1998, pp. 761-764, as well as R. Martel et al., *Applied Physics Letters,* 26 October 1998, pp. 2447-2449, and A. Hassanien et al., *Applied Physics Letters,* 28 December 1998, pp. 3839-3841, deal with so-called nanotube "transistors" with a bulk silicon gate. L. Venema et al., *Applied Physics Letters,* 3 November 1997, pp. 2629-2631, show a way of cutting nanotubes *in situ.* Z. Ren et al., *Science,* 6 November 1998, pp. 1105-1107, show a method of making large numbers of free-standing, aligned, and spaced carbon nanotubes.

DISCLOSURE OF THE INVENTION

It is therefore an object of the present invention to provide a manner of using nanotubes to provide devices of improved areal density, speed, stability, and uniform characteristics.

It is further an object of the present invention to provide a nanoswitch which can be made by using only slightly modified existing apparatus technology to manipulate nanotubes and other nanostructures to be positioned to within a few Å of where they are desired.

It is further an object of this invention to provide complementary switching devices on the same nanotube without any conventional "doping" or other structural modification to the nanotube *per se.*

It is a further object of this invention to produce a gating structure which will produce a localized electric field having a substantial field component directed along the nanotube longitudinal axis.

It is further an object of this invention to produce a nanoinverter circuit, analogous to that of the CMOS silicon circuit, to efficiently process signals.

It is further an object of this invention to produce a nanomultivibrator, or flip-flop, circuit analogous to that of the CMOS silicon circuit of the same name to efficiently process signals.

It is further an object of this invention to produce a nanomultivibrator, or flip-flop, count down chain to provide a means of quickly counting extremely high frequency pulses.

It is further an object of this invention to produce nanoswitches having a sharp, unparalleled high slew rate for switching, perhaps several thousand times faster than those of conventional silicon.

It is further an object of this invention to provide a high power switch and housing having unprecedented high slew rates and power handling capabilities.

It is still further an object of this invention to provide a structural manner of compensating for the RC time

constant gating lag in a power nanoswitch device so that the entire device will conduct at the same instant, thus providing an extremely high slew rate.

It is still further an object of this invention to provide a structural manner of compensating for the RC time constant gating lag in a power nanoswitch device so that essentially the entire device will conduct and essentially the entire device will shut-off at the same instant for each operation, thus providing a very high slew rate for both operations.

It is still a further object of this invention to provide novel atomic microscope probe designs capable of attracting and depositing nanometer sized objects in a highly precise manner.

It is still a further object of this invention to provide a novel manipulating apparatus head assembly for conventional atomic positioning microscopes so that an apparatus capable of picking up the device elements and carrying, manipulating, positioning, and depositing these device elements to extremely close positional tolerances, on the order of an Å, is achieved using only slightly modified existing positioning apparatus technology.

It is still a further object of this invention to provide an apparatus and method of separating, selecting, straightening, and cutting nanotubes to enable the other invention objects can be carried out.

Additional objects, features, and advantages of the various aspects of the present invention will become apparent from the following description of the preferred embodiments, which description should be taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A shows a a cross-section of conventional construction for one embodiment of a switching device using a nanotube with a bulk silicon gate, and Figure 1B shows the voltage-current characteristics thereof.

Figures 2A, 2B, and 2C show the present invention, as determined by the inventor, for a nanotube operating with a barrier having relatively high electron affinity under conditions of zero, positive, and negative biasing respectively.

Figures 3A, 3B, and 3C show a first preferred embodiment of the invention comprising a conducting nanotube and crossed gating member in isometric and cross sectional views, and the operating characteristics thereof, respectively.

Figures 4A, 4B, 4C, and 4D show a second preferred embodiment of the invention comprising a conducting nanotube with a surrounding gating material structure in isometric and cross sectional views, and three operational characteristics thereof, respectively.

Figures 5A, 5B, 5C, 5D, and 5E, show various process steps for making a nanotube inverter of the second preferred embodiment.

Figures 6A and 6B show a single nanomultivibrator, NMV, and a frequency dividing nanomultivibrator chain construction, respectively.

Figure 7 shows an isometric view of the end of a single conducting nanotube to be used in a power nanoswitch in a first preferred embodiment.

Figure 8A is an isometric view of the final power nanoswitch and housing with the top contact slightly exploded in a first preferred embodiment; Figures 8B and 8C show isometric and cross-sectional views, respectively, of second and third embodiments of a power nanoswitch with a second turn-off gating structure.

Figure 9A is a schematic of the equivalent gating circuit of the power nanoswitch, Figures 9B, 9C and 9D show suitable gating pulse shapes.

Figure 10 is a side view of a conical transportation probe in accordance with a first preferred embodiment of the invention and Figure 11 shows a side view of an elongated transportation probe in accordance with a second preferred embodiment of the invention.

Figure 12A shows an isometric view of a nanotube separation and alignment tank according to the invention, while Figure 12B shows a flat plate version of the same.

Figure 13 shows an apparatus for assembling and manipulating the nanoelements to form a nanostructure under computer control.

BEST MODE FOR CARRYING OUT THE INVENTION

When the term "nanotube" is used, this will be construed to not only include carbon nanotubes, but those made of BN, MoS_2, and any other material or composition capable of forming such structures having the appropriate electrical and mechanical properties.

A "nanostructure" will be any construed as any protein, chemical molecule, polymer, or any other structure of the order of the nanometer in at least one dimension. The conventional hexagonal graphene chiral vector indices for nanotubes are used, such as in M. Dresselhaus et al., *Science of Fullerenes and Carbon Nanotubes,* © 1996, Academic Press.

While nanostructures are capable of being understood perfectly only through the use of quantum mechanics, this involves extensive calculation and in many instances is not needed to understand the invention. Thus while the invention will be explained in conventional electrostatic terms for ease of use and understanding of the invention and in many cases this will be sufficient, the ordinary worker will appreciate that the invention can be easily recast into quantum mechanical formalism where ever necessary.

The Prior Art nanodevice at Figure 1A has some perplexing characteristics as shown at Figure 1B. The explanation at as R. Martel et al., and A. Hassanien et al., *supra,* that this is a device whose conduction is through "holes" does not adequately comport with the data. Most especially troubling is the experimental observation that as the gating voltage V_G becomes more and more negative, that the source-drain conduction current I_{SD} continues to increase for *all* source-drain V_{SD} voltages. Further, the off-hand explanation of "holes" is perhaps misleading. In silicon, an acceptor atom is "doped" to the silicon thus forming a mobile positive charge, but with charge neutrality of the silicon and the localization of the "holes." Here, since there is no actual "doping" of the nanotube, these "holes," if they exist at all, would be due to an actual charge imbalance in the nanotube, whose equilibrium would imply a very complicated and global solution of the electrical field equations, which would significantly change with the slightest biasing and would not lead to a clear understanding of how to use them in a useful manner.

Most importantly, however, since the nanotube has conducting electrons, upon close inspection these results are *exactly opposite* to what one would expect for the analogue depletion mode N-channel insulated gate field effect device in silicon that this device resembles. As seen below, the exact nature of this anomalous, but apparently unresolved result, will be explained in a model which more closely approximates the actual forces at play and more completely explains these anomalous results, and thus forms the basis for the model for this invention.

Figure 2A shows the novel analysis cross section of a nanotube under no gate bias, i.e. $V_G = 0$ according to

this model. From the inventor's analysis, here one sees the outer portion of the nanotube 140, the inner portion 141, the inherent free conduction electrons 142 of the conducting nanotube 140, the barrier material 143 acting as a gate insulator, and the gate electrode per se 144 connected to a source of gating potential V_G. The electron affinity, χ_b, of the gate barrier material 143, here an insulator, is quite critical and apparently is sufficient to fully deplete the electrons from the conducting nanotube 140 where it contacts 143 according to the inventor's analysis. Here about 8Å of the nanotube circumference contacts the barrier material 143 and is indicated by 145. Whenever a material rich in conduction electrons such as the nanotube contacts a barrier material having a sufficiently high electron affinity, χ_b, then electrons such as 146 will be drawn from the nanotube conductor 140-141-142 at 145 and be locally bound or trapped at the surface of contact, indicated here as 146 according to the inventor's analysis. This can leave behind fixed, immobile positive charge centers 145. A barrier material 143 surface having high electron affinity, χ_b, will, of course, induce greater attraction and thus more flattening and more charge transfer than one having a lesser electron affinity. The point is that for even small diameter conducting nanotubes 140, there will always inherently be a finite flattening and intimate interaction with the gate barrier material 143 it lies on in this model. In the above example, the tube is close to a (10,10) in size and thus a contact area of about 8Å would be expected on the sufficiently large electron affinity, χ_b, barrier material insulator SiO_2. SiO_2 has been notorious in the silicon field for the many dangling bonds inherent in its amorphous structure and has an electron affinity, χ_b, of about 0.9-1.0eV.

Typically one conventional way of passivating SiO_2 to remove these dangling bonds is to use hydrogen as a passivant; here the hydrogen offers up its electron to complete the bonds left unfinished by the SiO_2, thus forming a resultant composition commonly designated as SiO_2:H. This reduces the electron affinity, χ_b, of the SiO_2:H to below that of untreated SiO_2. Another even more effective way of removing the dangling bonds and reducing the electron affinity, χ_b, from SiO_2 is to use a fluorine treatment to react with any of the dangling bonds, this resultant product being commonly designated SiO_2:F. Especially this latter changes a normally relatively high electron affinity barrier material, SiO_2, into one having a relatively low electron affinity, because all the electrons at these dangling bonds will be firmly bound to the fluorine. Thus the electron affinity, χ_b, for fluorinated barrier layer materials is quite low.

Thus Figure 2A shows that perhaps 8% or so of the available electrons in the conducting nanotube 140 are trapped at the barrier layer insulator 143/nanotube 140 interface as indicated by 146 and are thus not mobile and do not contribute to conduction. In Figure 2B, however, a positive voltage is put to the gate member 144 of the device. Here, the free electrons 142 in the conducting nanotube 140 are drawn to the positive voltage and under the highest positive voltage, virtually all the free conduction electrons 146' are trapped at the interface between 140 and 143, and thus conduction drastically decreases. The application of a positive voltage to the gating member 144, then, under this model leads to the counter-intuitive experimental result that conduction goes down, as is shown experimentally in Figure 1B.

Applying a negative voltage to the gating member 144 as at Figure 2C shows just the opposite effect; the applied gating voltage overcomes the inherent electron affinity, χ_b, of the barrier layer insulator material 143 to eject the trapped electrons 146" back into the conducting portion of the nanotube 140 and thus increases the number of electrons available for conduction in nanotube 140. Indeed, this is shown at Figure 1B where the conductivity increases about 8% or so upon the application of a V_G = -6V bias to gating member 144 for a source-drain V_{SD} bias of 100mV. Application of a relatively high negative voltage is thus not seen to pinch off the conduction channel, as

would be expected in a conventional silicon circuit, due to the fact that the conducting nanotube 140 and the gate are substantially co-linear and there is no longitudinal electric field component in the direction of the nanotube axis by which electrons may be removed. Thus, by symmetry, no "pinch-off" can be effected. The electric field is entirely normal to the gating insulator 143 surface over its almost entire extent, thus providing no "escape" for the electrons in the conducting nanotube 140.

The nanoswitch then acts as a highly non-optimized pseudo P-channel depletion mode switch even though the conduction is not with holes, in this model, but with electrons. It is called "pseudo" because it externally acts like a silicon P-channel device, even though the actual internal workings according to this charge trapping model are quite different. Again, this is counter-intuitive to that which might be expected for a silicon device, but shows important features and differences from that of the conventional silicon structure discovered by the inventor: carbon nanotubes can act as an equivalent pseudo P-channel silicon device when there is a barrier layer between the conducting nanotube and the gating member structure having a sufficiently high electron affinity, χ_b, to deplete the mobile carriers from the conducting nanotube. Nanotubes, following the teachings of the invention, can do this as well, but by merely by changing the electron affinity, χ_b, of the barrier material at the gating member/nanotube interface at selected locations. Thus a single nanotube can be constructed with two blocking regions of different electron affinity, χ_b, and have all the advantages of the complementary silicon device in a much more compact arrangement. In silicon, a well region of the opposite conductivity has to be made; this is totally eliminated in nanotube technology in accordance with the invention. Thus while a silicon CMOS inverter, for instance, might have a chip area ~μm^2, a nanotube inverter might have a size area ~$4nm^2$, a difference of 250,000 times smaller area. This is felt to be a significant improvement in device density.

The gating member and the particular design of the blocking layer between the gating member and the conducting nanotube of the invention can be any of several equivalent constructions, depending upon the particular materials desired to be used in the construction.

For purposes of illustration, a first embodiment in the form of an N-channel depletion mode nanotube switch is proposed as at Figures 3A, in isometric form, and at Figure 3B, in cross section along the conducting nanotube 151, as shown. This term "conducting nanotube" is used to denote a nanotube which is capable of being biased by a potential difference, +V and Ground, or equivalently Ground and -V, at removed portions of the conducting nanotube 151 and through which a conduction current may pass, the modulation of such a conduction current being controlled by a gating structure 150, to which a suitable control voltage V_G is to be applied. The "conducting nanotube" 151 may be one of several different constructions, as noted below, and is not limited to the "metallic" nanotubes; it can also be a single wall or a multiwall nanotube. A second, gating nanostructure 150, which can also comprise a nanotube, and having different characteristics from the first conducting nanotube 151, is crossed with the first conducting nanotube 151. It also can comprise a single wall or multi-wall nanotube.

Here in this first preferred embodiment, the different properties, such as the control of the blocking layer electron affinity, χ_b, belong to and are associated with the gating member 150.

This is illustrated at Figures 3A and 3B where conducting nanotube 151 is crossed with gating member 150 which member can comprise either a single structure 150 or a composite structure comprising one or more inner layer nanostructure(s) 152 and an outer layer of barrier material of predetermined electron affinity, χ_b, 153 around its outer periphery, the composite structure of 152 and 153 also referred to together as gating member 150.

A barrier material 153, including a high electron affinity, χ_b, barrier layer material, can create a good N-channel depletion mode device since the contact depletion area between conducting nanotube 151 and gating member 150 is so small as to be neglected in this construction. If, for instance, the barrier layer material 153 is conductive, such as a Schottky forming metal, or a semiconductor, or a doped semiconductor, or a combination of semiconductor layers, then it can be used with an inner gating structure nanotube 152 even though the barrier material of 153 has a high electron affinity, χ_b, and may completely deplete the carriers from that inner nanotube 152. In this case, the inner gating member nanotube 152 acts as a non-conducting structural support member or mandrel for this high electron affinity, χ_b, barrier layer material 153 in the gating member structure 150.

One particular combination of a high electron affinity, χ_b, material useful in gallium arsenide (GaAs) integrated circuits is the use of a combination layer of undoped GaAs over the inner nanotube 152 and an outer layer of N+ doped AlGaAs over the undoped GaAs layer. This produces a two dimensional electron gas, "2DEG," just inside the GaAs at the GaAs/AlGaAs interface and provides a highly conductive means by which the gating potential signal V_G to the gating member 150 can be propagated down the gating structure 150. This, then, can form one of many "bridges" between a GaAs integrated circuit and a nanotube integrated circuit. Alternatively, the highly doped N+ AlGaAs layer can contact the inner nanotube 152 and the GaAs layer be on the outside of the N+AlGaAs. Further, such nanotube/GaAs(N+AlGaAs)/N+AlGaAs(GaAs) combinations could have utility in their own right as completely compatible conductors for power and signals in a hyperfine GaAs integrated circuit by itself.

If, as is shown at Figures 3A and 3B, the barrier layer material 153 of the gate member 150 has an electron affinity, χ_b, sufficiently small so as to not completely deplete the electrons from a nanotube and has a sufficient barrier height for gating isolation purposes, then a successful depletion mode N-channel nanoswitch can also be had with a much wider range of materials. Here the conducting nanotube 151 will hardly notice the presence of this low electron affinity barrier layer material portion 153 of the gating member 150 when there is zero biasing voltage V_G put to the gating member 150. The electrons in the conducting nanotube 151 are then free to conduct as well as the electrons in the gating member 150. When a sufficiently negative gating voltage V_G is put to the gating member 150, however, by Coulomb electrostatic repulsion, the electrons in conducting nanotube 151 will be repelled and depleted in the region illustrated as 154 in the entire area adjacent to the contact between the conducting nanotube 151 and the gating structure 150 and current flow in the conducting nanotube 151 will cease. This transfer characteristic is shown at Figure 3C, where at a negative gating voltage $V_G = -V_{Nth}$ the conducting channel pinches off at this threshold voltage and the conduction stops. The slope of the I/V_G curve at $-V_{Nth}$, the "switching slew rate" of the gate, $\overline{\Delta I/\Delta V_G}$, is moderately sharp as only an extremely small gating voltage V_G difference is needed to fully deplete the conducting nanotube 151 diameter. A point of difference here to the prior art is that the entire conducting portion of the gating structure 150 produces an electrostatic surface which has an electric field E at the depletion layer surface 154 having a longitudinal component E_L along the conducting nanotube 151 longitudinal axis and a transverse component E_T normal to the longitudinal axis. The simplicity of this design is that it can be made completely of elemental carbon nanotubes, all of which have been made for years by laboratories throughout the world. If the conducting nanotube 151 is a semiconducting nanotube of bandgap g_1, then the gating structure 150 can be another semiconducting nanotube, for instance, with a second bandgap g_2 significantly different from g_1, $g_1 \neq g_2$. Thus for an N-channel depletion mode nanoswitch a wide range of combinations of true metallic, metalloid, or semiconductor nanotubes can be used, including the conductive nanotube 151 and the gating structure 150, and a wide range of materials can

also be used for the barrier material 153, the only provision being that the barrier between the conducting nanotube 151 and the gating member 150 have a sufficient barrier height to provide a usable gating voltage V_G to the gating member 150 to fully deplete conducting nanotube 151 without breakdown or adverse leakage.

As above noted, the structural design of Figures 3A and 3B is not well suited for a pseudo P-channel nanoswitch, basically because of the small area of contact between the conducting nanotube 151 and the barrier material 153 of the gating structure 150. One solution, of course, is to increase the level of contact of the barrier material with the conducting nanotube, such alternative construction shown at Figures 4A and 4B. It is preferred in this embodiment that the barrier material 153' substantially surround or completely surround a region of the conducting nanotube 151' to give the device this sufficient contact area. If the barrier material 153' is not inherently sufficiently conductive to form an equipotential surface when contacted by gating member 150', an additional conductive layer 157 can be added to surround the barrier material 153' and the conductive nanotube 151'. For many materials, such as Schottky barrier materials which are inherently sufficiently conductive as noted above, this added conductive layer 157 may be unnecessary and preferably is omitted as long as the gating member 150' can make ohmic contact to the conductive Schottly barrier material 153'. The gate threshold voltage $V_G = -V_{Pth}$ is a direct result of the workfunction ϕ_b of the particular barrier material 153'. The only requirements here for this barrier gating material 153' is to have a sufficiently large electron affinity, χ_b, to at least partially deplete the conducting nanotube 151' at zero gating bias V_G whether the conducting nanotube 151' is a true metallic, a metalloid, or a semiconducting nanotube, and with sufficient barrier height so that a practical potential barrier can be established sufficient to undeplete the conducting nanotube 151' at a proper gate voltage $V_G = -V_{pth}$ as is shown by switching curves 167, 168. A further pseudo P-channel nanoswitch, a depletion mode device, may also be made using this construction of Figures 4A and 4B. If the barrier material 153' is able to trap electrons but has an electron affinity, χ_b, which is insufficient to deplete, or fully deplete, the electrons from the conducting nanotube 151' at zero gating bias V_G, then by applying a positive gating potential V_G to the gating structure, this positive potential may be able to assist the barrier material 153' to then trap the free electrons in the barrier material 153' and thus pinch off the conducting nanotube 151'. This case is shown with the dashed curve 169 at Figure 4C. Thus a device of narrow conduction can be had as at Figure 4D.

These are all the elements needed to form a pseudo "CMOS" nanotube switching pair inverter which can have all the advantages of the silicon CMOS pair where the gates of the N-channel and pseudo P-channel nanoswitches are connected together to the same negative V_G switching signal, one way as at Figure 5A. Here a beginning nanotube 171 is coated with a beginning barrier material layer 173 which has a sufficient electron affinity, χ_{b1}, to deplete the beginning nanotube 171 of carriers at zero external potential bias, a material which has been discussed as above. A masking, dummy nanotube 175 of suitable lateral width is then placed over a portion of this beginning barrier material layer 173 as illustrated at Figure 5A. An ion-implantation of a particular ion is then done to convert the beginning barrier material layer 173 into a second barrier material layer 174 having a second electron affinity, χ_{b2}, which is insufficient to deplete the conducting nanotube 171 of carriers at zero biasing potential, as discussed above, at the unmasked portions. Since it is preferred that this second barrier material layer 174 completely surround, or at least substantially surround, the conducting nanotube 171, this can be done by moving the ion source in a 180° arc using the longitudinal axis of the conducting nanotube 171 as an axis of rotation. Thus by using the temporary nanotube 175 as a mask and implanting the desired ions in such a 180° arc, virtually all of the

unmasked portion of the initial barrier material layer 173 is converted to the new material 174. One particular example of this is to use uncompensated SiO_2 as the beginning barrier material 173, which as noted above has sufficient electron affinity, χ_{b1}, to deplete carriers from the conducting nanotube 171, as has been previously noted. If hydrogen, H+, or fluorine, F-, ions are then implanted into the unmasked portion and suitably heat treated, as in conventional silicon processing, then that barrier material portion 174 will have a second electron affinity, χ_{b2}, which is insufficient to deplete the carriers from the conducting nanotube 171, as previously discussed. Here, since the barrier material layers 173 and 174 are insulators having different surface properties they are detectable and the transition between the two is detectable by a Tunneling Electron Microscope ("TEM") probe 176 as is illustrated at Figure 5B. It is well known in the art that a voltage put to such a probe can, depending upon the applied voltage pulse, e.g. less than 4 volts, generate a high enough electric field to clear away the insulator 173-174 at this transition portion 178 as is shown at Figure 5B. The entire assembly can then be overcoated by a conductive coating 177 and the TEM probe brought back as at Figure 5C where the probe 176 can again detect the transition portion 178 and can blast the conductive coating away at this portion 178 with a voltage pulse. A bias can then be put to the conducting nanotube 171, the tube assembly put into an electroetchive bath, and the portions of the conductive layer 177 which are in direct contact with the conductive nanotube 171 will etch away first, leaving a conductive coating 177 only over the barrier material portions 173 and 174, as is shown at Figure 5D. One alternative variation of this process is to use an appropriate Schottky forming metal for the initial barrier material 173. Here ions of another type of metal can be then implanted into the exposed portion of 173 at Figure 5A to alter the alloy composition thereof. The gating member 170 corresponds to that of 150 and 150' of Figures 3A - 4B and, due to the coextensive nature of the conductive overlay 177, forms the common gate of the N-channel depletion mode nanoswitch 171-174-177 and the pseudo P-channel enhancement mode nanoswitch 171-173-177. Thus at Figure 5E the conductor nanotube 179 contacts the conductive nanotube 171 at the node between the P and N-channel devices and forms the output signal of the inverter, the conductor 177 forms the common gating connection, and the gating member 170 forming the signal input. Thus a very compact pseudo CMOS type inverter can be made using all of the same type of conducting nanotube 170 without any doping of the conductor member and done in a very compact arrangement, the entire length kept to about 50Å or so.

Using this CMOS-like nanoinverter of Figures 5E, it is a simple matter to form a cross-coupled nanomultivibrator, NMV, (flip-flop). One can take two of the nanoinventers of the construction of Figure 5E and rotate one of them 180° with respect to the other such that the gating and output connections are aligned as at Figure 6A. Here the nanoinverter at the left has the same designations as that of Figure 5E. The rotated nanoinverter at the right has the same designations, only primed ('). Thus the input conductor nanotube 170 of the nanoinverter on the left is connected to the common node of the nanoinverter on the right, 179' and a single conductor nanotube 170-179' then forms this essential cross-coupling. In a likewise manner, the common node connection 179 of the nanoinverter on the left is cross-coupled connected to the output gating 170' of the nanoinverter on the right. While the terms "-V" and Ground are used to denote the potentials to the various regions it is to be noted that they can equally be considered to be Ground and +V, respectively, this being a change only in what one chooses to call a "ground." Since the gating voltages here are negative to achieve the desired switching, then the first designation, Ground and -V, may be more accurate. However, since conventional engineering has used +V and Ground, for such CMOS inverters, this designation can also be used equivalently.

If one uses a (10,10) metallic nanotube for the initial conducting nanotube 171, adds a barrier layer 173-174 of about 30Å thickness, and a final conductive coating 177 of about 10Å, then the inverter of Figure 5E will have a diameter of about 50Å and can be about 50Å long. Assuming a spacing between the two nanoinverters of about 15Å, one has a cell pitch of about 130Å x 75Å, or about 100nm^2 in total area for the nanomultivibrator, NMV. This is perhaps a factor of 10^8 smaller in volume than any multivibrator currently being made.

An estimate can be made of the performance of the nanomultivibrator. Since the capacitance, C, of a conductive wire above a conductive substrate can be shown, e.g. at W. Scott, *The Physics of Electricity and Magnetism, 2nd Edition,* © 1966 Wiley, New York, pp. 163-165, to be:

$$C = 2\pi\varepsilon_o L/\ln\{(d + (d^2 - R^2)^{\frac{1}{2}})/R\}$$

where $\varepsilon_o = 8.85 \times 10^{-12}$ F/m, $d \approx 25$Å is the distance from the conductor axis to the plane, $R = 6.5$Å is the conductor radius, and considering the length of the nanoinverter at ≈ 50Å and the length of the output line to the other inverter at ≈ 130Å, then a total capacitance, C, of the one nanoinverter node becomes $C \approx 2 \times 10^{-18}$ F. Considering that the tested resistance of such nanotube conductors is in the range of 400 - 750 Ω/Å of length on a macroscopic average, then the 180Å total inverter and output resistance length results in an RC time constant on the order of $RC \approx 0.1$-0.3×10^{-12} sec., or in the sub picosecond range, somewhat faster than current silicon devices. This estimate has been independently corroborated by calculations of A. Johnson at the 1999 I.S.S.C.C., and others for similar structures.

A plurality of such nanomultivibrators, NMV, as in Figure 6A can easily be combined in a chain to form a count-down frequency divider. If one takes the basic design of Figure 6A and forms an adjacent multivibrator unit of a mirror image construction, then this will result in like pairs of adjacent conducting nanotubes having the same power supply connection as at Figure 6B with a plurality of such mirror-reversed nanomultivibrators, NMV^i, in a counting chain, except for the end nanoinverters. One can then put two long conductor nanotubes 190 and 190' over the regions corresponding to the nodes and input/output connections. To form the cross-coupled connections for each nanomultivibrator, NMV, merely bring back the TEM probe and go to every fourth space between the conducting nanotubes 190 and 190' and apply a voltage, ranging from 4 to 6.5 volts, to it which is sufficient to sever the nanotube 190, 190' at that point. See, for example, L. Venema et al., *Length control of individual carbon nanotubes by nanostructuring with a scanning tunneling microscope,* Applied Physics Letters, Vol. 71, No. 18, 3 November 1997, pp. 2629-2631. This cutting is marked with an "X" in the drawings. Thus rather than bring in short sections of nanotubing to form the cross-coupled connections corresponding to 190, 190', single long sections can be used and then broken in situ as desired and as indicated. Thus, applying the input signal to the input and the appropriate power supply voltages, one can have a nanomultivibrator, NMV, frequency dividing chain of any desired length in a space far smaller than is possible with any techniques today.

It will be appreciated that power devices play an important role in the electronics industry and that devices having extremely high switching slew rates are currently quite useful in such areas as telecommunications and power transmission. Using the design of the pseudo P-channel device of Figures 4A and 4B, however, one can readily adapt this design to that of a power device.

Conducting nanotubes can be used to have all the advantages with none of the disadvantages associated with the conventional silicon technology for such a proposed power device. If a plurality of conducting nanotubes, ranging from several, to dozens, to hundreds, to millions, to hundreds of billions, whether they are true metallic, metalloid, or semiconducting, are placed in parallel and suitably gated, then a power device can be constructed. The

chief object of the gating member 150' in Figures 4A and 4B is to provide a potential to a single conducting nanotube 151'. By merely connecting a plurality of nanoswitch tubes together in parallel with a common gating and common end connections, a nanoswitch of lowered ON resistance and increased power handling capability is enabled. In the very large power device embodiment of Figure 8A, the gating is to be done macroscopically throughout the power device, so many of the particular limitations and restrictions on the gating member 150' of Figures 4A and 4B can be relaxed.

This modification of the nanoswitch of Figures 4A and 4B to a very large power device structure is shown beginning at Figure 7. Conducting nanotube 241, whether it is a true metallic, metalloid, or semiconducting nanotube, is surrounded by a barrier material 243 and a conductor 247. If barrier material 243 is a conductor, then 243 and conductor 247, if it is used, are preferably recessed at the ends of conducting nanotube 241. Otherwise if barrier material 243 is a dielectric insulator, it can be made flush with the ends of the conducting nanotube 241. As with the embodiment of Figures 4A and 4B, the barrier material 243 can be any Schottky forming material, or insulator, or semiconductor material, including III-Vs and II-VIes, of whatever kind and doping, etc., such that the electron affinity, χ_b, of the barrier material 243 is sufficient to deplete or at least partially deplete the conducting nanotube 241 at zero gating potential V_G while providing sufficient gating barrier height to provide a usable gating function for a gating control voltage V_G. Conductive material 247 need only provide a gating potential surface to the barrier material 243 and can, in some instances, be part of the barrier material 243. The only requirement is that the conductive material 247 or, if used alone, the barrier material 243 be sufficiently conductive to provide a relatively low gating RC time constant for the gating signal V_G and can form part of the Schottky barrier material if the Schottky barrier is chosen. However, as will be separately shown below, even this RC time constant requirement can be compensated for as well to effectively null-out any such RC time constant delays in a very large power device to enable all the elements of the power switch to completely switch at the same instant, thus providing a power switch of unprecedentedly high switching slew rate.

While there are, of course, many different methods of making carbon nanotubes, and this invention is not directed to such processes per se, some of the processes result in tangled ropes of nanotubes and these processes are not directly applicable to being used with most of the invention. However, one example of compatible processes which has great applicability to all the modes of the invention practiced here is that of Z. Ren et al., *Synthesis of Large Arrays of Well-Aligned Carbon Nanotubes on Glass*, as appeared in Science, Vol. 282, No. 5391, 6 November 1998, pp. 1105-1107. Here free-standing aligned and spaced carbon nanotubes are grown up to several square centimeters at a time on a nickel-coated glass substrate. Especially Figure 3B thereof shows essentially a forest of spaced nano-telephone poles. This particular process, which has the nanotubes separated, makes possible the use of standard silicon processing technologies such as Chemical Vapor Deposition ("CVD") techniques for a variety of dielectric, semiconductive, and conductive materials as are used herein. Any prior art method which provides for the separate formation of the nanotubes so they can be treated with conventional silicon technologies is applicable here. Using such a nanotube creation method allows for the later formation, for example, of an uncompensated SiO_2 or SiO_x barrier material 243 on the surfaces of the carbon conducting nanotube 241 using wholly conventional silicon processing technology.

In practice, any number, from several, to dozens, to hundreds, to millions, to hundreds of millions of billions of these conducting nanotubes 241 are collected together into a bundle. If the method of Z. Ren et al., *supra*, or any other similar method is used, then after the various depositions are performed it is a simple matter to slice or harvest the tubes from their substrate and create aligned sub-bundles or groups of them for further bundling and integration. If the outer conductor 247 of each conducting nanotube 241 is made of gold or other highly conductive material, then these conducting nanotubes 241 can be formed together into a bundle or group sub-bundle with the respective ends of the conducting nanotubes being connected together. For a large, very high power device a large macroscopic bundle can be used, shown for illustrative purposes at Figure 8A. Here a "hockey puck" type shape housing is shown for the collected bundle 251 of conducting nanotubes 241, since this is a common power device package. The pseudo P-channel enhancement mode power nanoswitch device 259 comprises the collective bundle 251 of conducting nanotubes 241 and an outer gating electrode band 250 which connects all the conductor portions 247 of all the conducting nanotubes 241 together to a first common terminal G_1. Conductive upper plate 258, shown lifted somewhat from contact with the conducting nanotube 251 bundle, and conductive lower plate 257 contact both the top and bottom surfaces and the exposed ends of both ends of the conducting nanotube 251 bundle. If the final diameter of the each conducting nanotube assembly as at Figure 7 is on the order of 60Å, then in a 4 inch diameter (100 mm.) diameter "puck" there will be a bundle area of 7.8×10^{17} Å^2, requiring about 2.48×10^{14} conducting nanotubes. If the resistance values of the nanotransistors of the prior art are accurate in that a conducting nanotube of usable length has an individual resistance on the order of a megohm (10^6 Ω), then this P-channel power nanoswitch has an ON resistance of 4.0×10^{-7} Ω. For a conduction of one hundred thousand amperes (10^5 A), the voltage drop across the nanoswitch is then 0.04 V, a value far less than any comparable conventional solid state switching device can achieve, at only 4 KW power dissipation. Further, since the pseudo P-Channel enhancement mode power nanoswitch of the invention is symmetric it can be used with AC as well as DC current and has no "turn-off" latching problems, a feature not commonly found with silicon power switches. This pseudo P-channel power nanoswitch can thus be useful for power transmission and power conversion purposes.

Further, the gating slew rate of this device, to first order, would normally be expected to be extremely sharp, based on the characteristics of the individual conducting nanotubes 241. However, since the first gating terminal G_1 to the gating ring 250 is off-set from the conducting bundle 251, there will inherently be a lateral as well as radial asymmetry of the gating signal pulse transmission from first gating terminal G_1 of 250 to the individual members of the conducting nanotubes 241 across the entire device. This is shown at Figure 9A. Here the turn-on gating signal G_1 is realized to not have an infinite slew rate, but in practice a finite slew rate. A finite slew rate gating signal put to gating input gating ring 250 through first gating terminal G_1 must pass through the conductive material 247_1 surrounding the most adjacent conducting nanotube members 241_1. The turn-on gating signal is then transmitted to the next adjacent set of conducting nanotubes 241_2 through their surrounding conductive material 247_2. The gating signal put to first gating G_1 input to 250 is then transmitted to the next adjacent set of conducting nanotubes 241_3 through their conductive materials 247_3 and on to the most distal group of conducting nanotubes 241_4 through the conductive material 247_4. If the gating ring 250 is very highly conductive, then the grouping of the most electrically distal conducting nanotubes 241_4 will be at the approximate center of the hockey puck package. Since the gating of the individual conducting nanotubes 241 involves the barrier material 243 there will always inherently be a capacitance between the conducting nanotube 241 and the first gating circuit to 250 and G_1. Thus

there will always, inherently be an RC time constant delay between the application of a turn-on gating pulse to the external terminal G_1 of the gating circuit ring 250 and the transmission of the same to the various portions of the pseudo P-channel power nanoswitch assembly 259. Thus the extremely high slew rate which these nanoswitches can individually exhibit would be largely diluted by such practical gating RC time constant concerns.

However, the effects of the time constants of the invention can, through a judicious choice of threshold values of the various sections and groupings of the power nanoswitch nanotubes, be adjusted so that the switching threshold V_{th1} of the conducting nanoswitch section 241_1 most adjacent to the first input terminal G_1 has the highest threshold, the threshold of the next nearest conducting nanoswitch section 241_2 has a lower switching threshold V_{th2}, etc., until the conducting nanoswitch section 241_4 which is most electrically distal to the first input gating signal at G_1 will have the lowest threshold V_{th4}. In operation, a judicious choice for the finite gating voltage slew ramp will result in a simultaneous higher gating voltage at 241_1 than at 241_2, which will be greater than at 241_3, which will be larger than at 241_4 at one specific time. By judicious choice of the gating slew rate and/or gating slew rate shape and the various thresholds, all the individual nanotube sections will then fire at the exact same time. Additionally the gating slew rate and gating pulse shape can be adjusted for a particular device to minimize the time differentials between the various sections and thus optimize the device. While only four sections are shown here for illustrative purposes, it will be appreciated that any number of sections, hundreds or thousands, can be formed so that the gating RC time constant can be adjusted and compensated for to any degree desired. Thus the extremely high switching slew rate of the individual conducting nanotube switch can be preserved to any degree desired in the final pseudo P-channel power nanoswitch. This then forms a power switch having a conduction slew rate of unprecedented degree.

The gating threshold V_{th} of the various sections can be controlled by any means known in the art, such as varying the thickness of the insulator, or any other means. If an insulator is chosen for the barrier material 243, then the insulator thickness can be changed from batch to batch, so that within a single batch it is uniform from end to end of any individual conducting nanotube 241, and uniform from individual conducting nanotube 241 to individual conducting nanotube 241 within that particular batch. By forming a plurality, perhaps hundreds or more, of separate batches of conducting nanotube switches with such different properties, a library of nanotube switches with their finely gradated thresholds can be created so that the engineer can design a nanotube power switch of predetermined properties and characteristics. Further, equivalent threshold voltage adjustment means can include the nanotube diameter. Other threshold adjustments include forming alloys of very finely divided and differentiated composition for the Schottky barrier material for the barrier material 243 to adjust the work function, ϕ_b, and forming a library of these nanotube switches with their different thresholds.

Figure 9B shows a constant slew rate gating pulse for such a power device where RC time constant concerns are not inordinate and can adequately compensated for by varying the threshold values of the various nanotube groups 241_x. However, for larger devices, such as the proposed 100mm. diameter device of Figure 8A, then a more shaped gating pulse can be used and in some cases is preferred. Here at Figure 9C the first part of the gating turn-on pulse has a very high slew rate drop from ground. This is so that the more distal portions can begin to be charged to bring the gating voltage up to almost the threshold voltage of the distal portions, thus "pre-charging" the more distal portions. After this very sharp drop in the gating pulse, the pulse drops more slowly to give the original portion of the pulse time to reach and charge the distal portions. The gating pulse is then chosen to drop to the adjacent group threshold V_{th1} just as all the further groups reach their respective thresholds and thus the entire

device switches ON simultaneously.

Such a power nanoswitch of Figure 8A can also be optimized for simultaneous turn-off, as illustrated at Fig.s 8B and 8C. Here, as at the second external gating input G_2 at Figure 9A, the groupings 241_4 nearest the external turn-off terminal G_2 have the lowest threshold voltages V_{th4} followed by the highest voltage threshold turn-off V_{th1} at the most distal portions from the external gate turn off electrode G_2 of the device. In such a case, a turn-off gating pulse to such an optimized turn-off device would be preferably shaped as in Figure 9D where the initial rise of the gating pulse toward zero is sharp with a high initial slew rate to almost the threshold voltages of the most adjacent groups 241_4 to allow transmission of the gating turn-off signal at G_2 to the most distal groups 241_1 to begin to "pre-discharge" them, followed by a lower slew rate so that when the most adjacent groups 241_4 of nanotubes turn-off all the other groupings to 241_1 will turn-off as well simultaneously over the entire power nanodevice.

One of the problems of the carbon nanotube technology up to now has been the inability to easily manipulate and separate the nanotubes. Being highly conductive, they have a high van der Waals force and are much like sticky cooked spaghetti on a dry plate, sticking to themselves and to their substrate.

Thus another aspect of the invention is to provide apparati for separating and positioning the nanotubes or any other nanostructures into the desired positions, to a level of a few ~Å. For over a decade, through such breakthrough work by Kasanuki et al., U.S. Pat. 5,418,771 and Yanagisawa et al., U.S. Pat.s 5,519,686 and 5,721,721, and many others, the atomic recording and microscope technology has built and perfected apparati designs which enable probes to be positioned over an X-Y plane to within an atomic diameter of a desired position, a few ~Å. Thus not only can such recording/microscope probes be positioned to a positional accuracy of an atomic diameter in an X-Y plane by such apparati, but they can also have the probes rotated as desired. Depending upon the desired major end function of these apparati they are variously called a "scanning probe microscope" SPM, "scanning tunneling microscope" STM, "atomic force microscope" AFM, "near field optical microscope" NFOM, etc., or any other such similar acronym which describes the use of such apparati to accurately control probes of various types and functions to an X-Y positional accuracy of a few Å.

One aspect of the invention is to use this basic probe positioning apparati of the prior art and modify it, using novel probe designs and novel probe head designs, to perform an entirely new and unobvious function of that of a nanomanipulator and nanotransporter for nanotubes and any other nanostructure such as proteins and individual molecules.

Figure 10 shows a first embodiment of this transporter probe. Here an initial probe 281, similar in generally conical shape to the TEM probes, has a spiraled conductor 282 extending from an upper portion of the cone to the tip or a portion near the tip. The upper portion 283 of the spiraled conductor 282 is connected to a source of electrical current. The initial probe 281 is a conductor and a thin layer of insulating material 285 with an extremely low van der Waals force material, such as a polymerized fluorocarbon, is put over the initial probe 281. A spiral conductor can then either be wound upon the surface of the insulated probe or a metal deposited upon it and micromachined or etched into the spiral pattern much like a metal film resistor. If wound, a nanotube can be used for the conductor due to their small size, great strength, and high conductivity. In either case, the spiraled conductor 282 can have a return conductor 284 applied to the side thereof. If a voltage is applied to conductive probe 281, then an electrostatic field is concentrated at 286 of the tip 287 and this can induce a switchable attractive force in nanomaterials, whether they be conductive or dielectric, below it. Also, if a current, including a time varying current, is placed to the spiraled

conductor 282, a magnetic flux field 286 can also be generated, achieving a maximum just below the tip of the probe 287 at 286. This assures that a conductive nanostructure, such as a gold or solder nanoball, can be picked up and properly transported to the desired end location and then deposited as desired.

For long nanomaterials, such as a long nanotube, a second embodiment to the novel transportation probe assembly is shown at Figure 11. Here the initial chisel shaped, laterally elongated probe 291 having a generally "V" shaped cross section has correspondence to that of 281 in Figure 10, with spiral conductor 292, conductor source 293, and return conductor 294 corresponding to those 281, 283, and 284 of Figure 10, respectively. Here the electric field and/or magnetic field flux is concentrated at 298 under the entire elongated tip 297 in an elongated manner, rather than in a point manner as in Figure 10. The length of this chisel probe width is sized to approximate that of the desired carbon nanotube length. This probe assembly of Figure 11 can be used to pick up the nanotube or any other elongated conductive nanostructure for transportation and deposition to where ever desired. This probe is especially intended to be used with a rotation means similar to that of 1111, 1112 such as is disclosed in Kasanuki et al., *Ibid.* Using this rotator, a nanotube can be picked up with the length aligned with the length of the transportation probe 291 and then rotated into any other angular position desired for transportation or deposition at the final site.

In either of the embodiments of Figures 10 and 11 the current put to the spiral conductor 282, 292 can be DC, sinusoidal AC, or a triangular sawtooth, or any other such waveform having sufficient AC component. At low levels, an AC signal can be used to detect whether the nanostructure, such as a nanotube, has been properly attached to the probe by monitoring the "detuning" of the circuit, or in a "fine wire" Eddy current detection mode. For high AC levels, the probe can induce a repulsive force to throw the nanostructure to the substrate if it is conductive; if not, the nanostructure can be coated with a conductor, which can then be removed later, to achieve this repulsion. Thus a combination of electric and magnetic fields can attract, analyze, and deposit nanostructures of all kinds in a highly precise manner.

The inventor has also invented a method of solvating the nanotubes in a low van der Waals bath, such as fluorinated compounds, including fluorocarbons, to separate the tubes from each other and this forms an important part in the practical use of the invention. Even with a fluorocarbon solvent surrounding and separating a collection of nanotubes, however, there may be some sticking and there is still the problem of nanotube orientation.

Figure 12A shows a nanotube separator and alignment tank device 300. Here there is a tank 300 to be filled with a low van der Waals solvent such as a suitable fluorocarbon. The density and other properties of such a solvent is chosen to be approximately that of the particular nanotubes or other nanostructures with the solvent coating each so as to provide a good suspension of the nanotubes throughout the solvent bath 301. The tank assembly 300 is preferred to be an elongated trough with a roughly triangular cross-section. At one side of the tank assembly 300 is an elongated acoustic transducer 303 which is capable of generating planar acoustic waves in the solvent bath 301. The proper choice of the tank 300 shape, the frequency of the signal generator 304, and the particular solvent in the bath will result in planar standing waves to be formed in the separation and alignment tank assembly 300. In operation, the nanotubes are suspended in their solution and the signal generator 304 tuned to the proper frequency and with an amplitude which will not break or degrade the nanotubes. If the suspension is of the proper density, then the agitation provided by the signal generator 304 and the transducer 303 will separate all the nanotubes and be sufficient to bring nanotubes up to the surface of the solvent bath 301. The action of the planar acoustic waves 305

will gently nudge the nanotube 302 which comes up to surface so that it will be in the lowest energy state being in that central node. Thus the nanotube, even if bent somewhat initially, will straighten and be perfectly aligned with the longitudinal direction of the solvent tank 300 at that central node, the lowest energy configuration for such a nanotube.

Figure 12B shows a variant of this separator and aligner with a rectangular acoustic plate 300' which is fed at one end by the planar acoustic transducer 303 and signal source 304 as in Figure 12A and works in a similar manner to form planar acoustic nodes 302' where the nanostructures will lie oriented along 302'. This aligner-separator of Figure 12B can be used for other purposes than the enablement of the disclosed invention as well, i.e. for forming structural designs such as an I-beam member.

The last aspect of the invention is combining all these features together to form a practical means of transporting and positioning the nanostructres, including nanotubes, into the final nanostructure, inbcluding circuitry, desired. As was previously suggested, the invention uses the recording and microscopy probe positioning apparati of the prior art such as of Kasanuki et al. and Yanagisawa et al. in an entirely new manner for such nanotube transportation and nanotube placement purposes. One such modified apparatus according to the invention is shown at Figure 13, which combines the multiprobe, extreme accuracy of the Yanagisawa et al. probe positioning and reference probe apparatus with the probe rotation apparatus of Kasanuki et al. Here is a multiprobe head assembly 310 which locks all the probes 316, 315, 314, and 312 into a rigid, stable alignment with each other. As is common in the art, all the probes here have a vertical positioning ability, which is entirely conventional and is not shown. The nanotube separation and alignment tank 300, or plate 300', keeps a supply of nanotubes or other nanostructures ready. If several different types or lengths of nanotubes are needed then there can be a plurality of such tanks 300, one for each type of nanotube; only one is illustrated here for simplicity.

The head assembly 310 can contain the elongated transportation probe 312 of Figure 11 and the associated rotation and vertical position mechanism 311, the conical transportation probe 314 of Figure 10, a standard STM probe 315, and a further reference encoding STM probe 316. As in Yanagisawa et al. the probe 316 provides a reference positioning encoding for the entire head assembly 310. By having the reference positioning probe 316 go over a suitable encoding positioning medium 317, the entire head assembly 310 can determine its position in an X-Y manner to a few Å, as is taught by Yanagisawa et al. The substrate 318 is the integrated nanotube substrate and preferably has an electron affinity, χ, which is insufficient to deplete any nanotube which may be placed on it of its electrons and thus change its electrical characteristics; the substrate 318 still has sufficient van der Waals force to keep the nanotubes in their final position, however.

If there are a number of lengths of nanotubes to be placed, then there can be a plurality of elongated transportation probes 312 and their associated rotation means 311 on the head assembly 310, though only one is shown here for simplicity. The rotation mechanism 311 is controlled by rotation and vertical position circuit 321 which is controlled by a central computer 320. The transportation probe 314 is connected to sources of voltage and current 319' and to circuit monitors 319, as is head 312 with its associated sources and monitors 313', 313. Here one uses the "fine wire" Eddy current analysis in current sensor 313' to determine if only one nanotube has been properly attached, and attached properly lengthwise, to the elongated transportation probe 312 or not. If two nanotubes are mistakenly attached to the probe 312, then this will be indicated by the degree of detuning of the spiraled induction coil 292 of the transportation probe 312. The AC driving current can then be reduced, or otherwise adjusted, in an

attempt of dropping one of the nanotubes.

The computer 315 then, after being satisfied that there is only one nanotube and that it is properly aligned with the transportation probe 312, and in conjunction with the encoding positional probe 316, moves the transportation probe 312 to the predetermined position over circuit substrate 318, rotates the nanotube to the desired angle, and then deposits the nanotube in the exact desired position and angle by lowering the head and releasing the nanostructure. If small nanoballs are needed for making ohmic connections, etc., then the conical transportation probe 314 can be used in a like manner.

The standard STM probe 315 is then run over the building up of the nanocircuit on substrate 318 to check for positional accuracy of the various nanotubes that have been placed so far. The standard STM probe 315 can then nudge the various nanotube assemblies back into proper alignment, as necessary. Further, as has been mentioned above, voltages ranging from 4 to 6.5 volts can be applied to the standard STM probe 315 to cut nanotubes, or a reduced voltage applied to clear unwanted dielectric and other coatings away in specific portions.

One further modification of this apparatus is if large numbers of a specific type of nanocircuit are to be built, then the reference medium 317 can have permanent markings put in it so that the apparatus can rapidly slew to the next position and then set up for the placement of the next elements. Further, this apparatus can be manually operated, or can be programmed to run unattended by itself through central computer 320, human intervention being necessary only for the filling of the various separation and alignment tanks 300, much as is done in conventional automobile manufacturing.

Thus it has been demonstrated that by using modifications to existing technology, in many cases using it for an entirely different and unobvious purpose, that nanostructures, such as nanotubes, can be made into N-channel and pseudo P-channel devices, that these can be combined on the same nanotube, that simple and complex logic gating and counting circuits can be constructed, and power devices of superior performance built easily. The invention, as stated above, is not limited to nanotubes and nanocircuits, but can include any nanostructure such as DNA, proteins, polymers, chemical molecules, etc., which need to be transported and arranged in a particular manner. Thus by using the teachings of the invention any practitioner is easily enabled to make and use the invention.

INDUSTRIAL APPLICABILITY

The invention has applicability in electronics, instrumentation, computers, biology, medicine, chemistry, power distribution and conversion, and high strength structures suitable for aeronautical and space craft.

WHAT I CLAIM IS:

1. A nanodevice comprising:

at least a first nanotube which is capable of conducting a current when a potential difference is applied to separated regions thereof; and

at least a first gating structure in conjunction with said at least a first nanotube at a first location for controlling the conduction current in said at least a first nanotube, said at least a first gating structure and said at least a first nanotube having a first barrier between them sufficient to sustain a gating potential when applied to said at least a first gating structure to control said conduction current,

said at least a first gating structure further comprising at least one of:

a. a second nanostructure generally transverse to and crossing said at least a first nanotube and having said first barrier therebetween;

and

b. a third nanostructure substantially surrounding at least a first portion of said at least a first nanotube and having said first barrier therebetween.

2. The nanodevice of claim 1 wherein said at least a first gating member comprises said second nanostructure which includes a second nanotube; and

said first barrier comprises a material selected from one of a dielectric material, a Schottky material, and a semiconductor material, said first barrier being placed between said second nanotube and said at least a first nanotube;

wherein said second nanotube further includes one of a true metallic, metalloid, and semiconducting nanotube, and

said first barrier material includes SiO_x, $x < 2$; SiO_2; SiO_2:H; SiO_2:F; fused metal oxides; fluorocarbon polymers; Hf; Mg; W; Pt; Ir; Ni; Pd; Rh; Mo; Cr; Ti; V; Nb; Ru; Sb; Os; Ta; Ge; Se; GaAs/N+AlGaAs; Si; III-V semiconductors; II-VI semiconductors; and nanotube semiconductors.

3. The nanodevice of claim 1 wherein said at least a first gating structure comprises said third nanostructure, said third nanostructure having an outer conductive surface, and

said first barrier comprises a material selected from one of a dielectric material, a Schottky material, and a semiconductor material,

said first barrier having a first electron affinity, χ_b, sufficiently large such that said at least a first nanotube is at least partially depleted of carriers at zero voltage bias applied to said outer conductive surface of said at least a first gating structure;

said first barrier material includes SiO_x, $x < 2$; SiO_2; W; Pt; Ir; Ni; Pd; Rh; Mo; Cr; Ti; V; Nb; Ru; Sb; Os; Ta; Ge; Se; GaAs/N+AlGaAs; Si; III-V semiconductors; and II-VI semiconductors.

4. The nanodevice of claim 3 further comprising at least a second further gating structure substantially surrounding at least a second portion of said at least a first nanotube at a second location and having a second outer

conductive surface; and

said at least a second further gating structure having a second barrier comprising a material selected from one of a dielectric material, a Schottky material, and a semiconductor material,

said second barrier having a second electron affinity, χ_{b2}, insufficient to deplete the carriers of said at least a first nanotube at zero voltage applied to said second outer conductive surface of said at least a second further gating structure;

wherein the thresholds of said at least a first gating structure and said at least a second further gating structure are set to the same voltage, said first outer conductive surface and said second outer conductive surface being electrically coupled together, a contact made to said first and second outer conductive surfaces for application of a signal input, and a contact made to said at least a first nanotube between said first and second locations for a signal output, to thereby create a nanoinverter of the signal input;

wherein said second barrier material includes $SiO_2:H$; $SiO_2:F$; fused metal oxides; fluorocarbon polymers; Hf; Mg; III-V semiconductors; and II-VI semiconductors.

5. The nanodevice of claim 4 wherein there is at least a second nanotube nanoinverter of substantially identical construction to said at least a first nanotube nanoinverter, both being on a common substrate, said at least a second nanotube nanoinverter being oriented at a 180° rotation to said at least a first nanotube nanoinverter, the two nanoinverters being thus antiparallel and spaced at a predetermined distance and longitudinally aligned such that said signal input of said at least a first nanotube nanoinverter is adjacent to the signal output of said at least a second nanotube nanoinverter, the signal input of said at least a second nanotube nanoinverter being longitudinally aligned with said signal output of said at least a first nanotube nanoinverter; and connections made between the two nanotube nanoinverters between these aligned pairs of inputs and outputs to form at least a first nanomultivibrator;

appropriate sources of potential to be applied to the free ends of said at least a first and second nanotube nanoinverters;

wherein at least one of such nanomultivibrators are formed on said common substrate in a given direction, the design of each nanomultivibrator being a mirror image of any adjacent nanomultivibrator along said given direction, the ends of all the nanotube nanoinverters of the adjacent nanomultivibrators of like sources of potential being grouped together in pairs for common connection; and

the signal output of one nanomulitvibrator being connected to the input of the adjacent nanomultivibrator along said given direction, to thereby form a frequency dividing chain circuit for said input signal.

6. The nanodevice of claim 3 wherein there are a plurality of said at least a first nanotubes,

said first barrier and said conductive surface of each of these plurality of nanotubes being generally coextensive with the length of each of these nanotubes;

said plurality of nanotubes forming a bundle and gating contact being made to said conductive surfaces of each of said plurality of nanotubes, said gating contact being connected externally to at least a first external gating terminal; and

first and second conductive electrodes, said first conductive electrode contacting the first ends of said

plurality of nanotubes at one end of said bundle, and said second conductive electrode contacting the second ends of said plurality of nanotubes at the other end of said bundle;

said first and second conductive electrodes being capable of being externally connected.

7. The nanodevice of claim 6, wherein

the threshold voltages of said plurality of nanotubes vary by groups depending upon the electrical distance from said at least a first external gating terminal, groups of said plurality of nanotubes electrically closest to said first external gating terminal having the highest threshold voltage, and groups of said plurality of nanotubes electrically most distal to said first external gating terminal having the lowest threshold voltage; such that

when a gating pulse of finite slewing rate is applied to said at least a first external gating terminal, the RC time constant of the propagation of the finite slew rate gating pulse put to said first external gating terminal is compensated for by the variation in the threshold voltages of the various groups of said nanotubes such that the entire nanodevice switches all said plurality of nanotubes simultaneously,

wherein the variation of threshold voltages of the various groups of nanotubes and the wave shape of the finite slew rate gating pulse are predetermined such that said nanodevice switches ON simultaneously over all said plurality of nanotubes from an initial OFF condition.

8. The nanodevice of claim 6 wherein,

said gating contact being connected externally to said at least a first external gating terminal at a first location of said plurality of nanotubes and a further second gating contact of said plurality of nanotubes being connected externally to a second external gating terminal at a location remote from said first external gating terminal;

wherein the threshold voltages of said plurality of nanotubes vary by groups depending upon the electrical distance from said at least a first external gating terminal to said second external gating terminal, groups of said plurality of nanotubes electrically closest to said at least a first external gating terminal having the highest threshold voltage, and groups of said plurality of nanotubes electrically most distal to said at least a first external gating terminal being simultaneously closest to said second external gating terminal and having the lowest threshold voltage;

such that when a gating pulse of finite slewing rate and particular shape is applied to said at least a first external gating terminal, the RC time constant of the propagation of the finite slew rate gating pulse put to said first external gating terminal is compensated for by the variation in the threshold voltages of the various groups of said nanotubes such that the entire nanodevice switches all said plurality of nanotubes ON substantially simultaneously; and

such that when a second gating pulse of finite slewing rate and particular shape is applied to said second external gating terminal, the RC time constant of the propagation of the finite slew rate gating pulse put to said second external gating terminal is compensated for by the variation in the threshold voltages of the various groups of said nanotubes such that the entire nanodevice switches all said plurality of nanotubes OFF substantially simultaneously; and

the variation of threshold voltages of the various groups of nanotubes and the waveshape of the finite slew

rate gating pulses applied to said at least a first and said second external gating terminals being predetermined such that said nanodevice switches substantially simultaneously over all said plurality of nanotubes in a quasi-optimized manner.

9. A nanotube separator and alignment apparatus comprising:

a nanotube separation and alignment medium;

an elongated acoustic transducer for producing acoustic waves along one edge of said nanotube separation and alignment medium;

a signal source connected to said elongated acoustic transducer for creating standing waves and standing wave nodes in said separation and alignment medium, so that nanotubes are separated and aligned along said standing wave nodes;

said apparatus further comprising one of:

a. an elongated tank with a predetermined cross section and filled with a low van der Waals force solvent;

said elongated acoustic transducer is positioned along one elongated side wall of said elongated tank; and

said signal source connected to said elongated acoustic transducer creates planar standing waves and at least one planar standing wave node in said low van der Waals force solvent; and

b. a rectangular plate with a low van der Walls force solvent;

said elongated acoustic transducer is positioned along one end of said rectangular plate;

said signal source connected to said elongated acoustic transducer creates planar standing waves and at least one planar standing wave node in said low van der Waals force solvent on said rectangular plate.

10. In an atomic microscope positioning apparatus, an improved head assembly for nanostructure X-Y axis transportation and manipulation, comprising:

a reference encoding STM probe for said improved head assembly and a reference encoding positioning medium used in conjunction with said reference encoding STM probe for determining the exact X-Y planar position of said improved head assembly;

a substrate for the construction of a nanostructure;

at least one probe in said head assembly for localizing at least one of an electric field and a time varying magnetic field directly beneath said at least one probe, and connected to a rotating mechanism, which mechanism is controlled by a rotating circuit,

said at least one probe additionally having one of a conical and a tapered chisel elongated shape, and said at least one probe being made of a conductive material with a contact and having an insulative covering and a helical magnetic coil thereover, and being connected to driver circuitry and drive current sensor circuitry,

a computer connected to said reference encoding STM probe, said driver circuitry and drive current sensor circuitry, to said at least one probe, and to said rotating mechanism and said rotating circuit,

whereby nanostructures, including nanotubes, can be picked up, manipulated, positioned, and set down in a predetermined manner to a desired location and position and with accuracy to within about an atomic diameter to form a predetermined nanostructure on said substrate in accordance with a predetermined program and programming instructions stored in said computer.
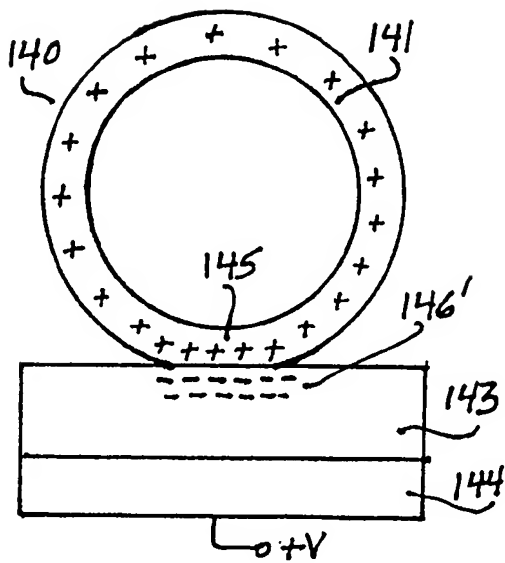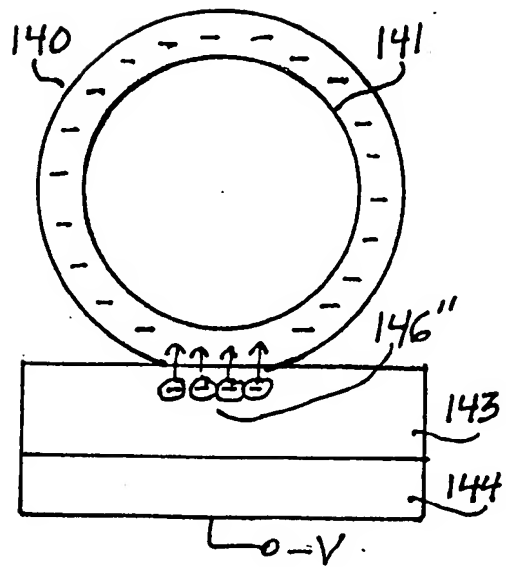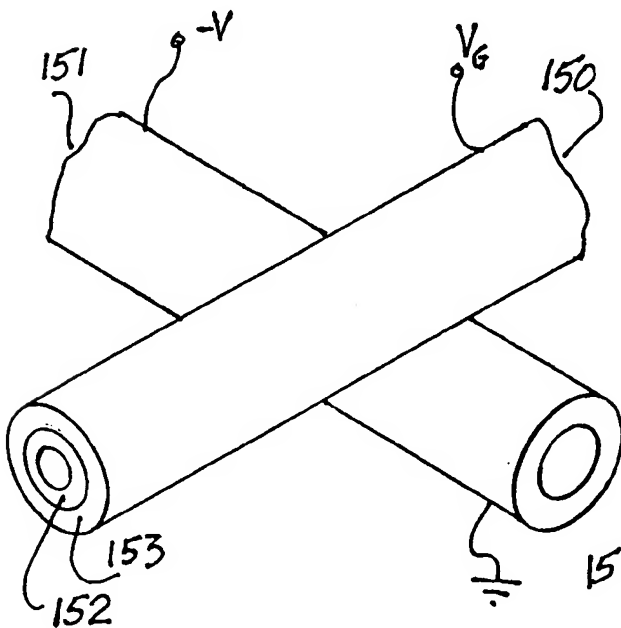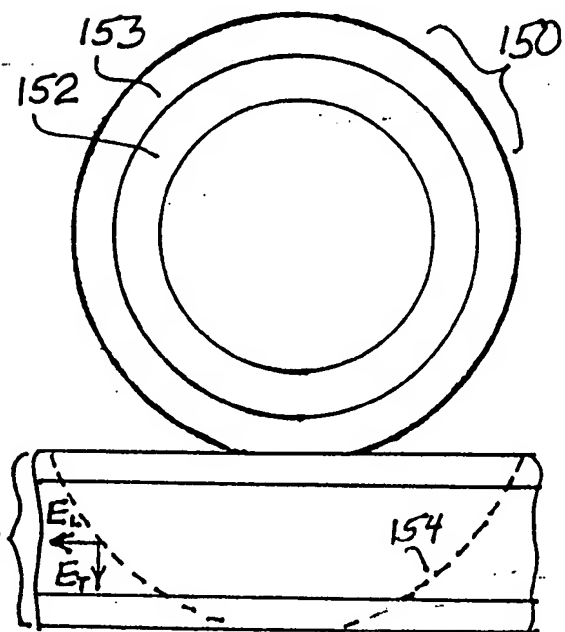
Fig. 5D

Fig. 1A   Prior Art

$I_{SD}(mA)$

$V_{SD} = 100mV$

$V_{SD} = 50mV$

$V_{SD} = 10mV$

Fig. 1B   Prior Art

Fig. 2A
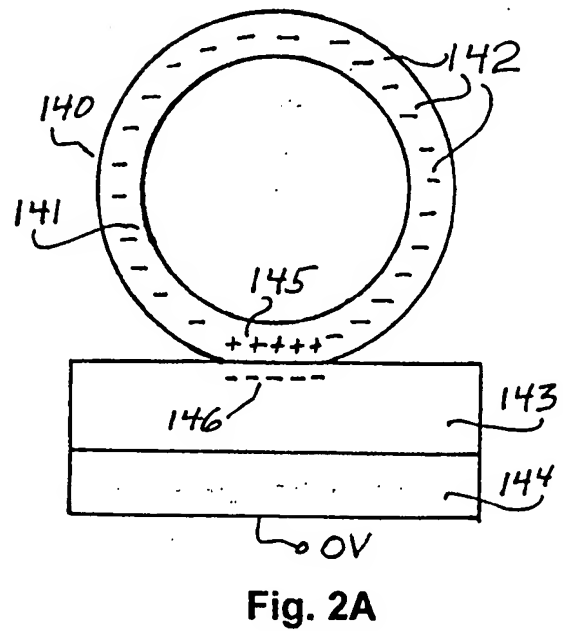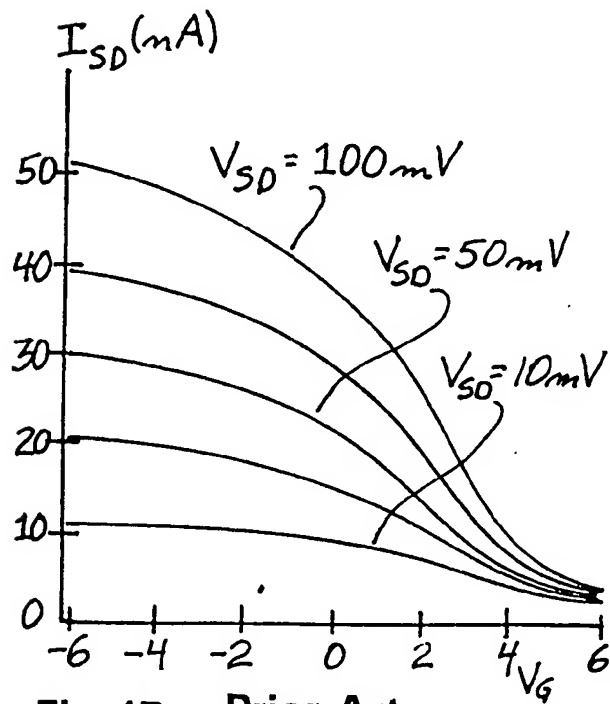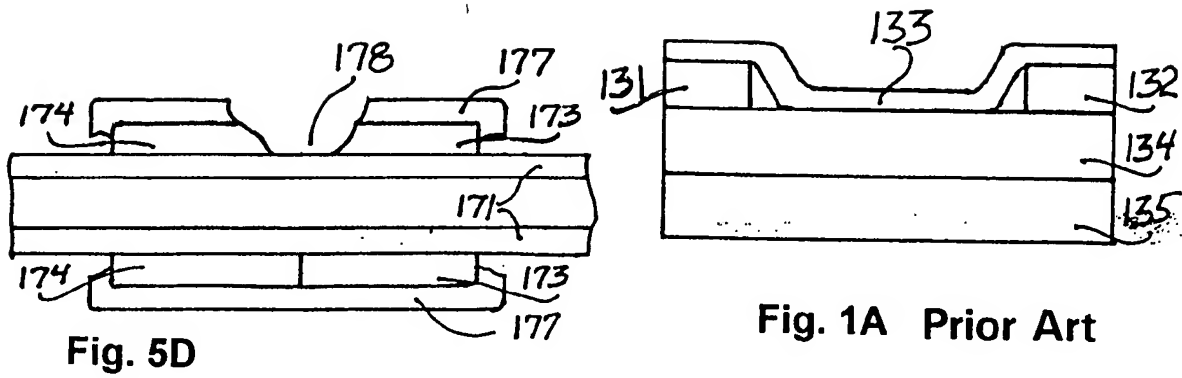
Fig. 2B

Fig. 2C

Fig. 3A

Fig. 3B

Fig. 4A

Fig. 4B

Fig. 3C

Fig. 4C

4/8

Fig. 4D

Fig. 5A

Fig. 5B

Fig. 5C

Fig. 6B

Fig. 5E

Fig. 6A

283   284   281

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286   287

Fig. 10

293   292   294   291

295

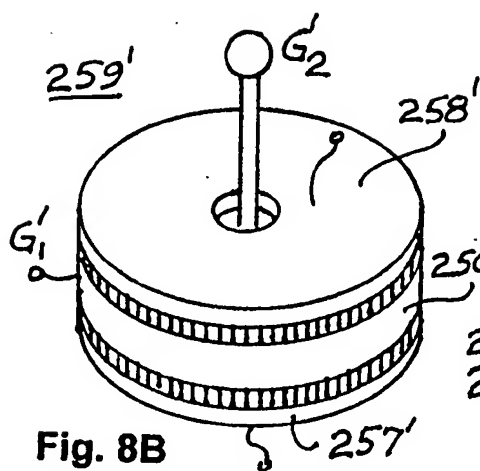297

298

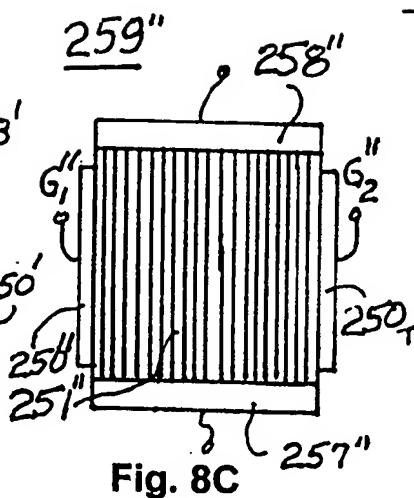**Fig. 11**

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243

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Fig. 7

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251   259

G(1)   250

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Fig. 8A
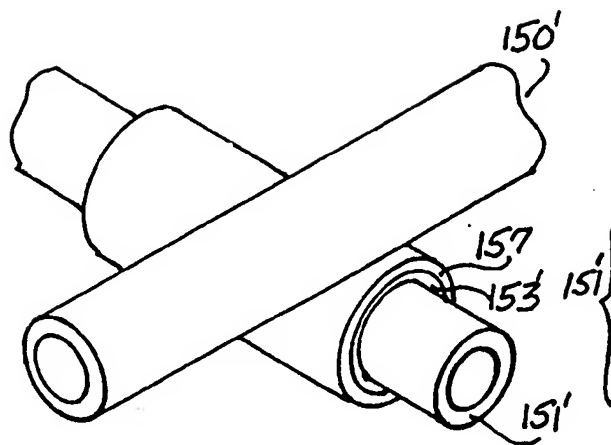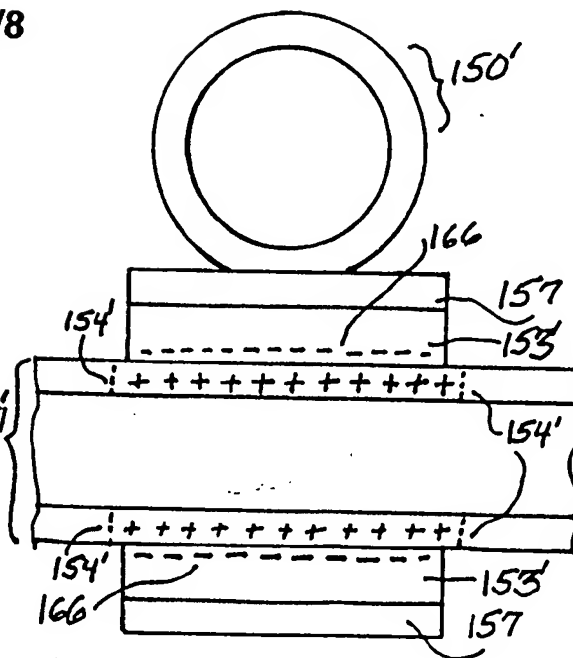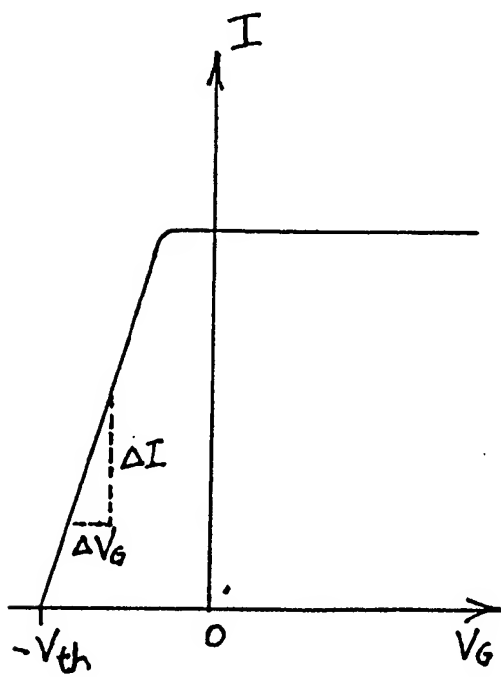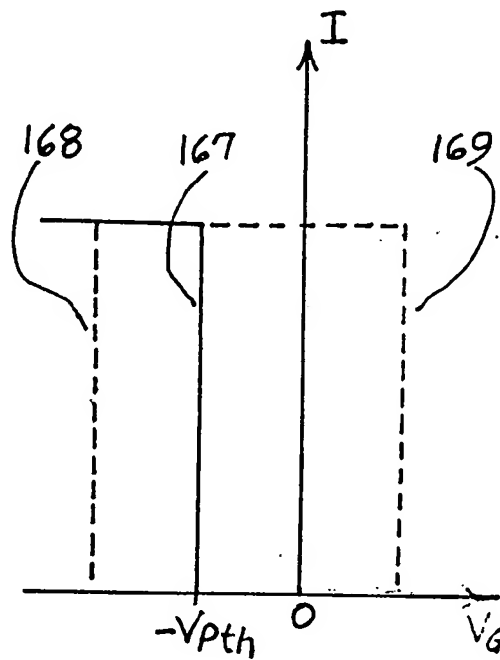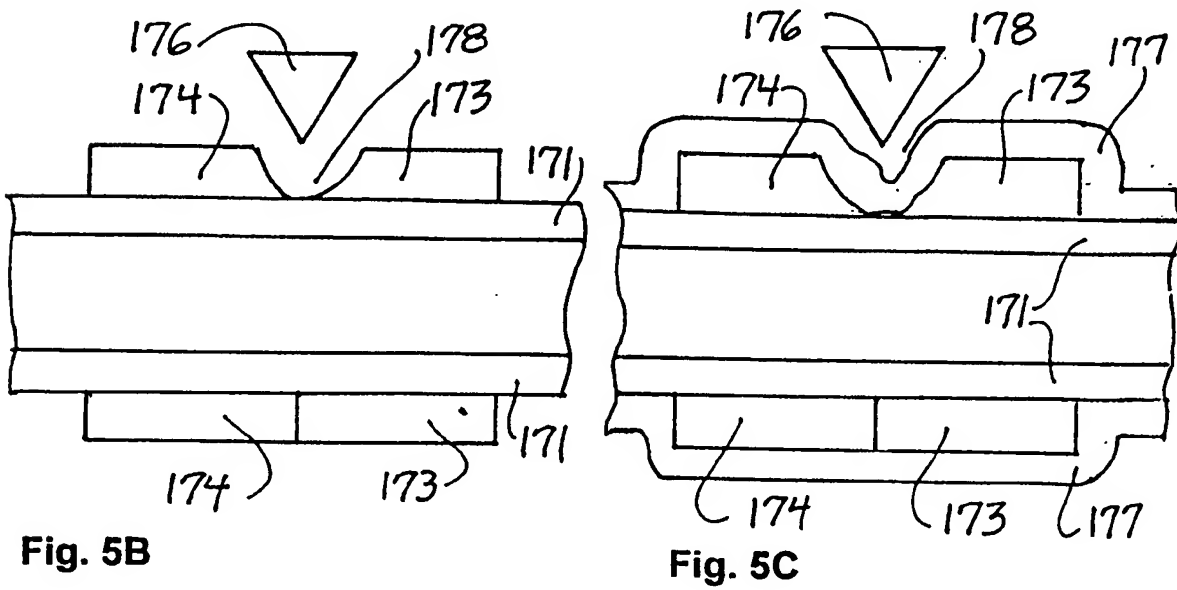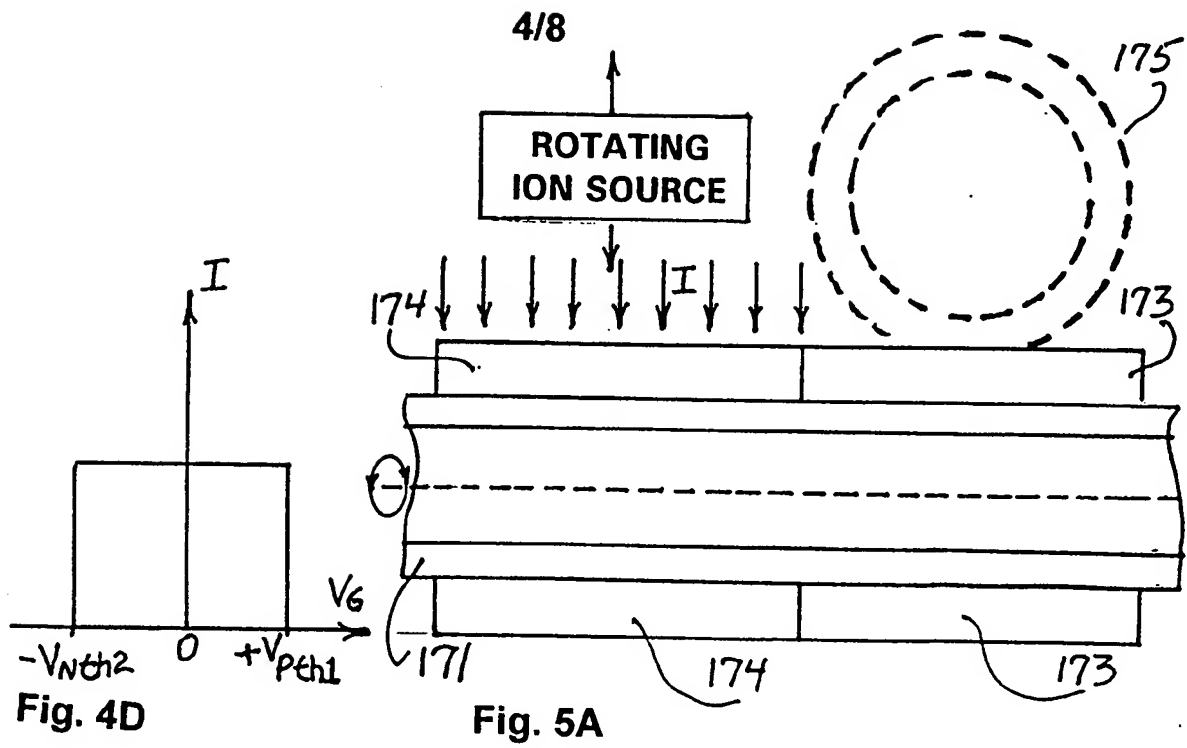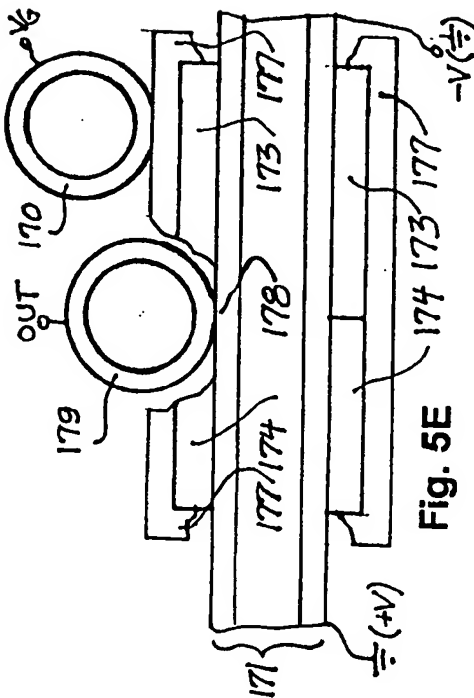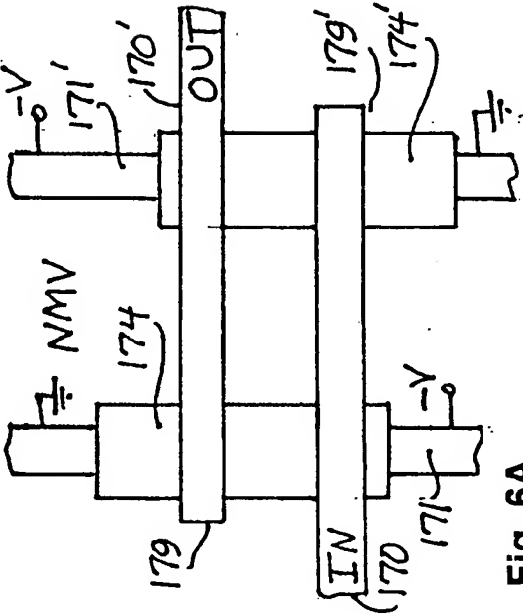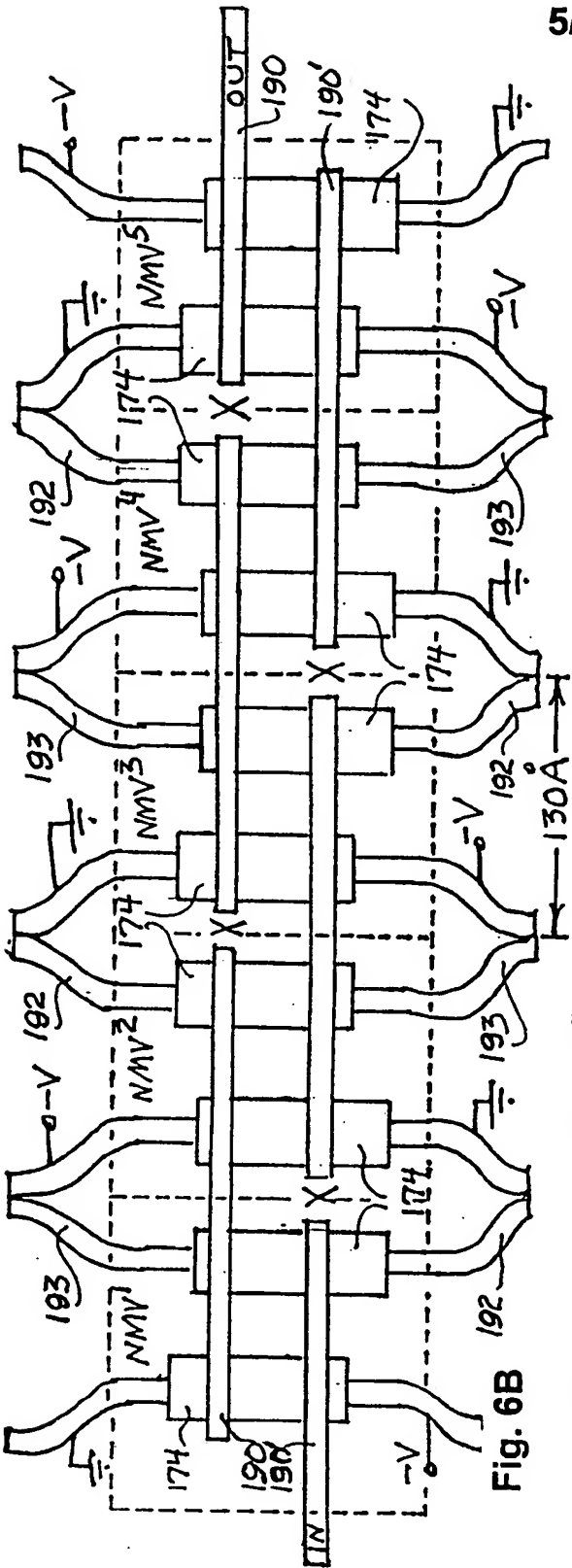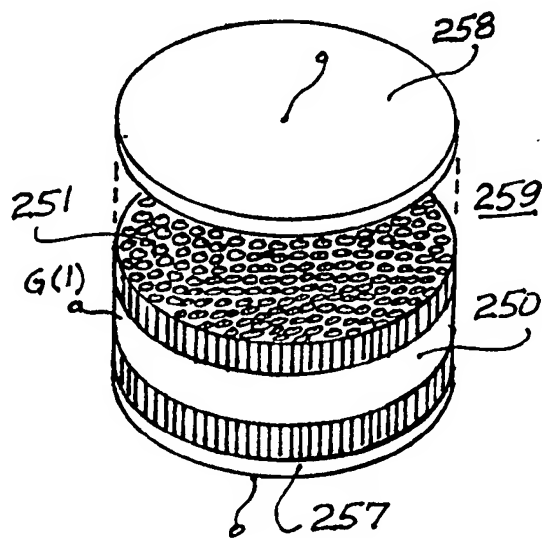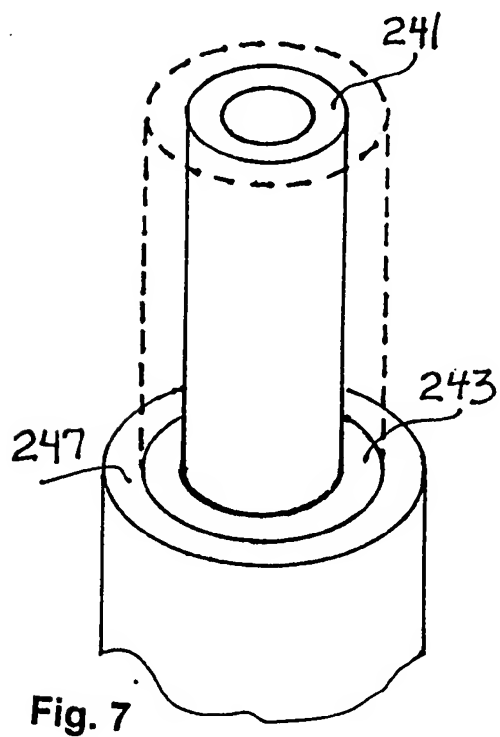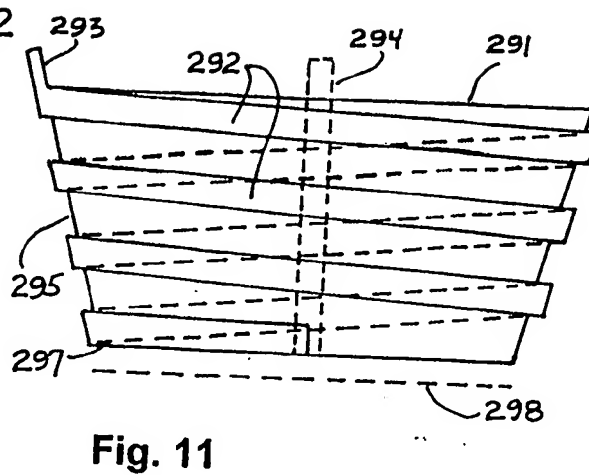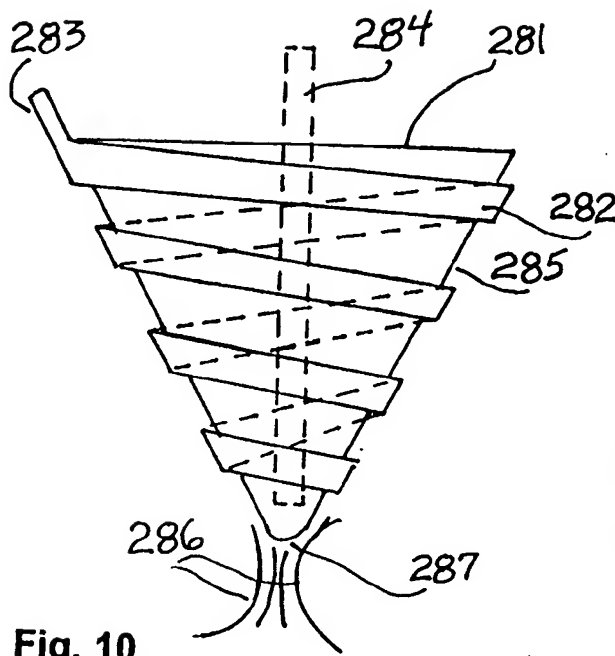
Fig. 8B

Fig. 8C

Fig. 9B
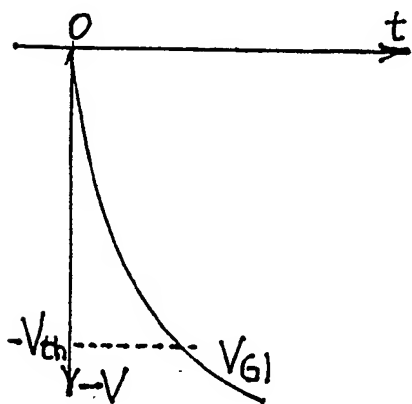
Fig. 9C
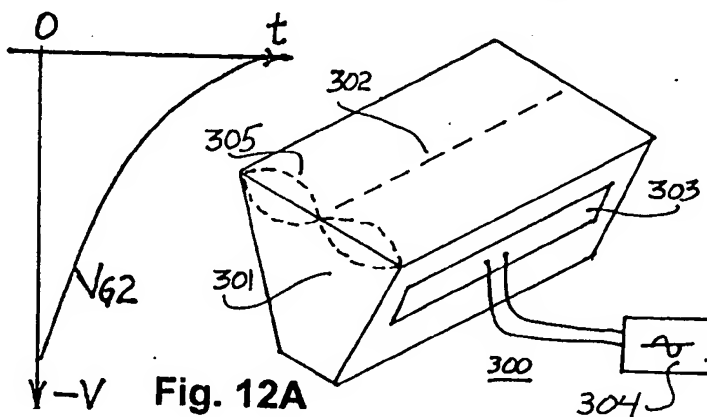
Fig. 12A

Fig. 9D
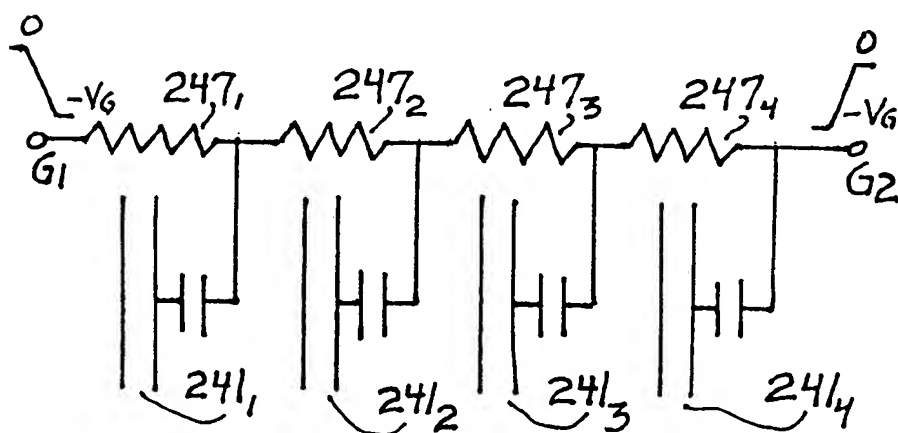
Fig. 9A
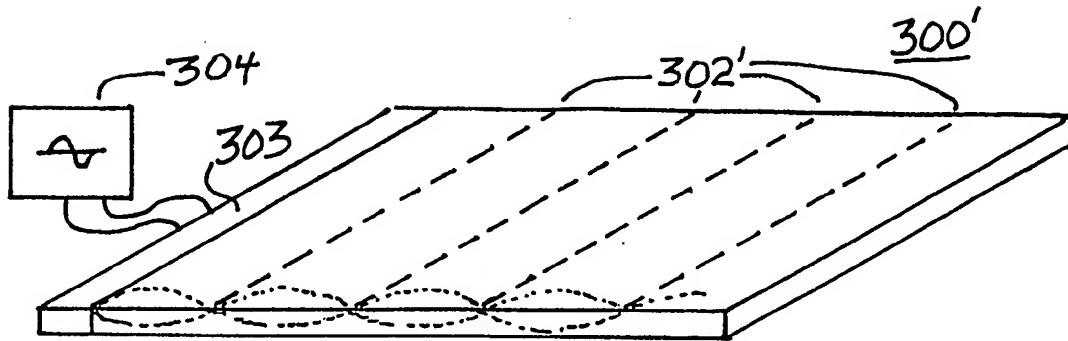
Fig. 12B

Fig. 13

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01L 29/06; B01D 17/06; G01N 23/00
US CL :Please See Extra Sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 257/9, 20, 22, 24, 27, 41, 213, 274; 210/188, 542, 748; 250/407, 442.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

IEEE TRANSACTIONS

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST, search terms: nanotube, gate, FET, acoustic separator, and STM positioning.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Martel et al., Applied Physics Letters, October 1998, Vol 73, No. 17, pages 2447-2449	1-10
Y	Menon et al., Physical Review Letters, December 1997, Vol 79, No. 22, pages 4453-4456, especially page 4455	1-10
Y	Tans et al., Nature, May 1998, Vol 393, No. 7, pages 4952, especially page 51	1-10
Y	Chico et al., Physical Review Letters, February 1996, Vol 76, No. 6, pages 971-974, especially page 973	1-10
Y	Pikus et al., Applied Physics Letters, Decmber 1997, Vcl 71, No. 25, pages 3661-3663, especially page 3663	1

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 JUNE 2000	06 JUL 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	TOM THOMAS
Facsimile No. (703) 305-3230	Telephone No. (703) 308-0956

Form PCT/ISA/210 (second sheet) (July 1998)

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Tans et al., Nature, April 1997, Vol 386, No. 3, pages 474-477, especially page 474	1-10
Y	US 5,831,166 A (Kozuka et al.) 3 November 1998 (03.11.98), col. 3, lines 39-47	9
Y	US 5,225,089 A (Benes et al.) 6 July 1993 (06.07.93), Fig. 1	9
Y	Venema et al., Applied Physics Letters, November 1997, Vol. 71, No. 18, paes 2629-2631, especially page 2630	10
Y	US 5,808,302 A (Binnig et al.) 15 September 1998 (15.09.98), Fig. 4	10

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US00/04220

Box I   Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II   Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

   Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest   ☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet(1)) (July 1998)★

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

257/9, 20, 22, 24, 27, 41, 213, 274; 210/188, 542, 748; 250/407, 442.1

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

Group I, claim(s)1-8, drawn to a nanodevice.
Group ii, claim(s) 9, drawn to an acoustic alignment device..
Group III, claim(s) 10, drawn to an atomic microscope which uses an

The inventions listed as Groups I, II an II do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: They are three completely different separate devices in three different fields.